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RECENT ADVANCES IN PARACHUTE TECHNOLOGY

by

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SUMMARY

Many new applications of the parachute have been developed in recent years. In addition to unconventional designs for emergency escape parachutes, sophisticated parachute systems have been used for recovery of space capsules and ram-air gliding parachutes for the delivery of men and equipment.

In the UK important advances have been made in the prediction of parachute inflation loads, in formulating design rules for ram-air gliding parachutes and in the use of new materials in parachute construction. Test techniques continue to improve and aircraft launched parachute test vehicles have become a reliable method of obtaining performance data. Progress is being made in stability analysis and new techniques devised for obtaining basic data.

The Memorandum is substantially the same as a lecture given to the Royal Aeronautical Society on 10 March 1983, at 4 Hamilton Place, London.

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1 INTRODUCTION

To the layman the parachute is often no more than a large pocket handkerchief which brings men safely to earth without a bump, but to the aeronautical engineer it is a complex aerodynamic decelerator, which has a large number of degrees-of-freedom and dynamic characteristics which are often difficult to account for by classical aerodynamic theory. Whichever view one may care to take of the parachute what is certain is that advances in parachute technology are nearly always a result of a balanced programme of both theoretical and experimental work, and for this reason equal attention will be given in this paper to both the experimental and theoretical aspects of parachute technology.

There are many types of parachute, in the same way as there are many types of aircraft, and for exactly the same reason, each type being designed and tailored to meet a particular requirement. Thus there is the flat circular porous fabric parachute, such as the Irvin PXI Mk 4, for paratroop use, shown in Fig 1a, shaped low porosity fast opening fabric parachutes such as the GQ Aeroconical for emergency escape from aircraft (Fig 1b), structurally strong ribbon parachutes such as the conical and hemisflow types for high speed weapon delivery, cruciform configuration parachutes for good stability (Fig 1c), and high performance ram air gliding parachutes for use in tactical assault operations by specially trained military personnel (Fig 1d).

In describing advances in parachute technology one is tempted at first to consider only the many recent spectacular advances in applications and types, ranging from the steerable highly manoeuvrable gliding parachute to the large sophisticated drogue and parachute cluster used in the United States to recover the Apollo crew module back to earth from space. But if a review of this kind was made it would be difficult to do justice to any one field. Rather the emphasis must primarily be on the more fundamental and scientific aspects of parachute technology in relation to the basic problems generated by the many applications of the parachute.

Thus in the design of conventional parachutes three general aspects of operation are important, inflation, stability and landing, but for the ram air parachute glide performance and control must also be taken into account. It is proposed therefore to take each of these aspects in turn and consider where technical advances have been made in recent years.

The problems involved will first be illustrated by presenting parachute performance data obtained in recent test work. Test techniques will also be outlined as reliable parachute data often requires the use of sophisticated and expensive full scale test techniques, such as the aircraft launched RAE parachute test vehicles, and in fact many of our recent advances have been made in the techniques of parachute testing[1,2]. A look will then be taken at the theoretical basis on which particular parachute behaviour can be explained and at some of the advances which have been made recently as a result of this combined work.

2 PARACHUTE INFLATION

Research aimed at improving our understanding of the factors governing the inflation characteristics and load/time history of parachutes has been taking place both in

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the United Kingdom and overseas for some years. One important aim of this research is to obtain an aircrew emergency escape parachute, for use in the next generation of ejection seats, which as well as having fast opening characteristics at low aircraft speeds also extends the allowable deployment speed up to at least 300 knots EAS and altitudes up to 5500 metres, without the parachute breaking up or applying more than 25 'g' to the man during inflation. The 25 'g' limit is fixed by physiological considerations and of course bulk and weight considerations limit the structural safety that can be built into an escape parachute. The last consideration is in fact true of almost all parachute installations and it must be remarked that it is a constant complaint of parachute designers, particularly where weapons parachutes are concerned, that far too often insufficient space is allowed to house a parachute expected to withstand high-speeds and inflation loads of many tons!

When considering parachute inflation it is first necessary to clearly distinguish between parachute and attached load combinations where the change of velocity during the inflation process is small, usually known as the infinite mass case, typified by the aircraft brake parachute, and those cases where the change in velocity during inflation is large; the finite mass case.

This difference is usefully illustrated by an ejection seat parachute system where it is a relatively simple matter to analyse the small seat drogue parachute which fairly closely represents the infinite mass case, but much more difficult to analyse is the case of the man on his large escape parachute where there is a considerable loss of speed as the man is rapidly decelerated during the actual inflation process.

Inflation load data for parachutes deployed at high-speeds can be obtained using the RAE parachute test vehicle air launched from a Canberra aircraft in the manner sketched in Fig 2. With this very useful experimental technique the vehicle is programmed to first deploy and inflate a small seat drogue parachute, which, after a short time delay, is then released to deploy the man carrying parachute under test, thus simulating the sequence of the Martin Baker ejection seat system. (It should be noted that the test vehicle is normally ballasted to equal the mass of a 99% man, plus his flying kit.) The vehicle is instrumented to measure deceleration due to parachute deployment and inflation, and a strain gauged link along the axis of the vehicle measures main parachute drag forces directly. Airspeed along the descent trajectory is measured by means of a pitot static probe fitted to the nose of the vehicle.

Fig 3 shows the peak opening loads determined using the test vehicle for the seat drogue parachute and for a GQ Aeroconical escape parachute, over a range of speeds, and at altitudes of 1500 and 20000 feet. Examination of the drogue data shows the peak load to increase in proportion to the 'lines taut' velocity squared, as would be expected, at both altitudes tested, and with a reduction in the peak loads at the higher altitudes. In this case comparison of the measured loads with the steady drag calculated for the speeds tested, multiplied by a small known opening shock factor gives excellent agreement. In the case of the man carrying parachute however the altitude effect is reversed and a similar calculation to that for the drogue gives a result which is some ten times greater than the measured value! Clearly the finite mass case requires special analysis.

Calculation of opening loads for the finite mass case has been investigated by several workers, for example Heinrich in America has developed a filling time theory[3], and Roberts has considered the interplay between fluid and system dynamics[4]. Both methods have their drawbacks, the filling time approach does not recognise the existence of external forces which can affect inflation, *eg* a drogue attached to the crown of the parachute, while Roberts' method makes considerable assumptions in the modelling of the fluid flow and parachute structure and involves complicated mathematics.

Dr Lingard at the Royal Aircraft Establishment (RAE) has recently pointed out that what in fact the parachute designer really requires is a simple theory which will enable him to rapidly obtain a good estimate of the peak inflation load and the shape of the load-time curve likely to occur in a particular deployment situation[5]. This would allow him to perform trade-off calculations upon the effect on inflation loading of various parameters such as the deployment lines snatch velocity, parachute diameter, mass of the suspended store, and altitude and flight angle of deployment. Reliable predictions of this type have the great advantage that they reduce the amount of expensive test work required on a particular parachute design.

Lingard has therefore made a detailed study of the factors determining opening loads. His analysis shows that a particular parachute design, of nominal diameter D_0, always inflates in a characteristic manner, and that the form of the load time curve is determined principally by the mass ratio parameter $M_r = m_s/\rho D_0^3$, where m_s is the suspended mass, as it is this ratio which determines the manner in which the trajectory velocity reduces during inflation. For a given mass ratio the peak inflation load is shown to be proportional to the parameter V_s^2/gD_0 where V_s is the lines snatch velocity (TAS). To use Lingard's method it is however first necessary to establish the unique force coefficient dimensionless time inflation characteristic, $C_F(\tau)$, of the parachute from one or two experimental results. Such data can however be quickly obtained from a simple form of parachute test vehicle dropped from a tethered balloon or from a single test using the air launched test vehicle.

The equations of motion of the inflating parachute and the suspended store are then written in the form

$$m_s\frac{dv}{dt} = m_s g \cos\theta - \tfrac{1}{2}\rho v^2 C_F(\tau) S_0 \qquad \text{and} \qquad \frac{d\theta}{dt} = -g\frac{\sin\theta}{v}$$

where v is the velocity along the trajectory, θ the trajectory angle, S_0 the wing area, and $C_F(\tau)$ the inflation force coefficient/dimensionless time relationship as determined by test.

The value of this analytical work, and its associated computer program for solving the equations for v and θ and hence inflation force over the inflation period, is illustrated by the graph at Fig 4, where the effect of a wide range of suspended mass on peak inflation force and peak store deceleration for the Aeroconical parachute (D_0 = 7.38 metres) is presented. For suspended mass in the range 80 to 135 kg (M_r = 0.16 to 0.27 at ground level), typical of aircrew plus various items of flying kit, the altitude effect previously noted from trials data (Fig 3) is predicted and the

overall values of store deceleration are in very good agreement with the trials data. As a matter of interest the calculations have been extended well beyond the normal range to a very high suspended mass of 10000 kg ($M_r = 20.4$) to demonstrate the effect of approaching the infinite mass case.

Similar calculations for different parachute diameters have shown that over the range of suspended mass of interest a larger parachute, giving a lower mass ratio, would result in a reduction in peak load. In fact as a result of computer studies of this nature a 5.8 metre flying diameter version of the parachute has been constructed and tests showed a reduction of peak load of some 30% compared to the original 5.2 metre design.

3 CONTROL OF INFLATION CHARACTERISTICS

In parallel with this work methods of automatically controlling inflation characteristics are being studied. A conventional escape parachute is often characterised by a very rapid increase in drag area towards the end of inflation which tends to lead to peak loads at this point (Fig 5). What is really required however, is a characteristic such that the maximum tolerable deceleration, consistent with human limitations, is applied rapidly and then held as steady as possible until a safe trajectory velocity is achieved. Considerable improvement in ejection seat performance, and in particular reduction of forward throw on the main parachute, is predicted if this ideal parachute inflation characteristic can be achieved.

The research approach has been one of building into the parachute features which modify its opening characteristics. For example attachment of the seat drogue to the crown of the main parachute by a bridle, which is a feature of the Martin Baker seat system, reduces the initial rate of opening of the main canopy and hence peak loads. In fact in RAE trials where the drogue was deliberately arranged to break away from the main canopy at 'main lines snatch' an increase of some 40% in inflation load was experienced. Encouraging results are also being obtained by work in conjunction with Irvin (GB) Ltd, on pressure relief valves, situated in the canopy crown, which burst at a predetermined speed to reduce peak internal pressures and hence inflation load.

It is interesting to note that a very sophisticated method of modifying the inflation characteristics of an escape parachute is incorporated in the Automatic Inflation Modulation (AIM) parachute developed in Canada by David Webb and his team at Irvin Industries, Ontario[6]. This parachute uses a combination of unidirectional stretch fabric in the crown area of the canopy plus a unique type of auxiliary parachute fitted in the mouth of the main canopy to control overall inflation time (Fig 6).

The small mouth parachute, called a Webb parachute, automatically remains in the centre of the mouth area throughout the inflation period, due to its geometry. The amount of control of canopy opening can be varied by altering the size and position of the Webb chute and obviously as deployment speed is increased so is the authority of this control. The purpose of the stretch fabric in the crown area is to vary the canopy porosity as a direct function of the dynamic pressure applied and hence to reduce peak loading.

Tests have already demonstrated significant advantages in control of inflation force, and maximum safe deployment speed at altitude compared with conventional round parachutes, and, although it is perhaps a complex design, there is little doubt that this type of parachute has a promising future.

4 PARACHUTE STRENGTH

Discussion of the parachute inflation process leads naturally to the subject of parachute strength since it is during inflation that the peak loads and stresses appear in the parachute structure. As a general rule a canopy will be subject to its greatest stress in those areas where the local radius of curvature is a maximum, when the differential pressure across the canopy reaches its maximum value; but without detailed knowledge of the load distribution it is impossible to assess what safety margins exist on the structure. Experience suggests that with parachutes designed to the simple stress formula given by Johns[7] and in the American Recovery System design guide[8], margins are adequate, but there is continual pressure to improve the structural efficiency of parachutes which has resulted in more sophisticated methods of stress analysis, such as the pressure-strain equilibrium approach embodied in the CANO digital computer program developed in the United States[9]. Unfortunately little detailed full scale test work to verify the predicted stresses appears to have been attempted, due mainly no doubt to the difficulties encountered in measuring fabric stresses under dynamic conditions.

The situation promises to be rectified however by use of the Omega gauge, developed in the 1970s, which can be glued on to textiles to measure stress directly, has temperature compensation incorporated, and is small enough not to be affected by local curvature[10].

As a result of the uncertainties of stress analysis it is often found necessary to determine the damage boundaries for a parachute by experiment, using the aircraft launched parachute test vehicle mentioned previously. In these tests parachute break up speed is determined by increasing the deployment speeds on successive drops until significant parachute damage occurs during inflation. A typical damage boundary obtained over a range of altitudes by this technique is shown in Fig 7.

When considering the subject of parachute strength, it must be noted that the use of Kevlar in highly stressed parachutes, particularly when stowage space is at a premium, has resulted in major improvements in structural efficiency. Kevlar is an aramid fibre manufactured by Du Pont de Nemours and Co. and is characterised by a high strength weight ratio. Kevlar 29 fibres have tenacities as high as three times that of nylon and a specific gravity of 1.4 compared to 1.1 for nylon. These two properties coupled together mean that it is possible to produce narrow woven fabrics from Kevlar 29 material at less than one-half the weight and approximately one-third the bulk of nylon materials with the same ultimate tensile strength. Furthermore Kevlar retains approximately half its strength at about 290°C, the temperature at which nylon fails. One important difference which affects detail design is the elongation of Kevlar under load, Kevlar stretching by only 4% of its original length before failing whereas nylon stretches by approximately 25%.

The principal use of Kevlar in the UK has been for small hybrid nylon/kevlar submunition parachutes and for the rigging lines of personnel parachutes, but in the USA a conical ribbon parachute of 12.5 feet diameter has been constructed in 'all Kevlar' with a weight and volume saving of some 50% of its equivalent nylon parachute and with no marked effect on opening loads or performance[11]. Only minor changes in the design of the canopy near the crown vent were required to accommodate the high modulus of Kevlar. Kevlar materials are more costly than nylon but the number of recent successful applications of Kevlar in parachute construction suggests that it will be increasingly used in future.

5 STABILITY DURING DESCENT

Another important area of parachute performance is the stability of the fully-inflated canopy and suspended store during descent. United Kingdom specifications for escape parachutes call for disturbances in descent to be damped, with any sustained oscillations not exceeding $\pm 15^{\circ}$ to the vertical, while for the airborne forces application $\pm 10^{\circ}$ is usually specified. This is not an exacting requirement compared to the stability requirements of some types of weapon parachutes but large oscillations increase the risk of ground impact injury to a parachutist and any improvements that can be made on personnel parachutes by simple methods are welcome.

It is well-known that the use of low porosity cloth in flat circular construction gives the rapid opening characteristics required of escape parachutes, but has an adverse effect on stability. Such a parachute will seek a non-zero angle of attack where it might glide, cone or oscillate in a statically, but not necessarily dynamically, stable condition. In this context a parachute is statically stable when any change in angle of attack is opposed by the aerodynamic moment developed, this being a necessary condition for stability, but the system is dynamically stable only when the restoring moments decrease the amplitude of each succeeding oscillation towards zero.

One simple modification which can greatly improve the stability of non-porous round canopies is the introduction of two or more asymmetrically disposed slots in the canopy to give the parachute a horizontal velocity (drive) in a defined direction opposite to the slot positions. Drive in personnel parachutes has the additional advantage that if steering lines are fitted to the slots the parachutist can then manipulate the slot areas and hence the flow through the slots to steer into wind to reduce ground speed or to avoid ground obstacles.

In some applications of a parachute, drive, or an angle of attack where the parachute tries to glide or oscillate, is an embarrassment and in these cases a well chosen configuration, such as a cruciform having a suitable arm ratio, can give very satisfactory stability while descending vertically. Research in the United Kingdom on very stable systems has in fact concentrated on this type of parachute as the design is simple to manufacture and has satisfactory opening and drag characteristics.

Detailed analytical investigations of the factors affecting parachute stability have been making steady progress at Leicester University over the last few years under research agreements sponsored by the RAE. A computer based six-degree-of-freedom

parachute stability model has been formulated by Dr Cockrell and his team and both wind tunnel and water tank measurements have been made on rigid and flexible scale model canopies to provide basic data for use in stability calculations.

An example of the type of wind tunnel data obtained at Leicester on canopies at different angles of attack to the airflow, is presented in Fig 8a. The simplifying assumption is made that for static stability analysis the centre-of-gravity of the canopy system lies at the rigging line confluence point[12]. The statically stable angle of attack is then that angle at which the pitching moment about the centre-of-gravity is zero and small disturbances result in a restoring moment, *ie* with the sign convention given on Fig 8a static equilibrium occurs when $dC_N/d\alpha$ is positive, resulting in $dC_M/d\alpha$ also positive (where C_N is the normal force coefficient and C_M pitching moment coefficient). The degree of static stability is then indicated by the slope of the moment curve at the trim angle.

On this basis the nil porosity round canopy tested can be expected to have a trim angle α of 38° and the 4:1 arm ratio cruciform to have good static stability at a trim angle of 0°, *ie* this canopy would descend along a vertical path (in zero wind conditions).

A further result obtained at Leicester, shown at Fig 8b, illustrates that by increasing the arm ratio of a nil porosity cruciform canopy the trim angle of attack is steadily reduced and that the desired characteristics of near zero mean trim angle is achieved only with an arm ratio greater than approximately 3.8 to 1; where the range of possible trim angles is decreased to $\pm 3^{\circ}$. (Arm ratio is defined as the length of an arm divided by its width - see Fig 8b.)

The theoretical work at Leicester has also stressed the importance of the apparent mass components in the equations of motion determining the parachute damping characteristics.

The apparent mass effect arises when a parachute, or any other body for that matter, accelerates through a fluid, as during an oscillation. For example, in accelerated linear motion not only is there a body inertia force equal to mf, where m is the mass of the body and f its acceleration, but also a fluid inertia force, due to the fluid accelerated by the body. This can be written as $m'f$ where m' is termed the apparent mass and hence the total force required can be expressed as $F = (m + m')f$. If $m = \rho_b V_b$ and $m' = k\rho_f V_b$, where V_b is the body volume and k is an apparent mass coefficient, it is seen that since the latter can be about 1.0 to 5.0, apparent mass has a considerable effect on body dynamics - if the density of the body is of the order of that of the fluid in which it is immersed. This is precisely the case with a large volume body such as a parachute and store, and hence the apparent mass components cannot be neglected in the equations of motion determining the parachute stability characteristics. There are of course other similar cases, of which the airship is a well-known example.

Yavuz, Cockrell and Jorgensen at Leicester have recently completed some very original experimental work to obtain apparent mass data for parachute canopies - which has provided valuable information. The technique employed force and moment measurement

during the accelerated motion of a model parachute submerged in water in a ship tank. Results show that the apparent mass coefficient depends on canopy shape, angle of attack, and on the acceleration modulus $\dot{v}D_0/v^2$ and, except at high values of the latter, can be considerably in excess of the values calculated from potential flow theory. As a result of the Leicester research programme on parachute stability the following conclusions have recently been drawn.

(a) Experimentally derived values of apparent mass components must be used in parachute stability calculations.

(b) The condition for static stability for a parachute is $dC_N/d\alpha$ positive. If $dC_N/d\alpha$ at equilibrium is large and positive this is also a sufficient condition for dynamic stability. However when considering the dynamic stability of canopies for which $dC_N/d\alpha$ is positive but small, a further necessary condition is that the apparent mass component along the normal axis must be greater than that along the centre line axis of the parachute.

(c) Dynamic stability is generally improved with increased altitude and increased store mass.

As part of a general programme of stability work RAE has conducted research in parallel with the Leicester programme aimed at providing data on the stability characteristics of fullscale canopies, using a specially instrumented stability test vehicle. This data is currently being used to validate Leicester computed predictions for a number of parachute designs.

Typical of this work is full scale data recently obtained on two versions of a 4:1 arm ratio cruciform configuration canopy which was shown to have excellent stability in vertical descent and low response to gust effects. Comparison of the experimental data with Leicester computer predictions is proving most encouraging.

6 LANDING

To avoid landing injury to a parachutist United Kingdom specifications for emergency escape parachutes call for a vertical rate of descent, at sea level, not exceeding 7.5 m/s, at maximum all up weight, while the figure recommended for airborne forces parachutes is a mean of 6.0 m/s. Permitted horizontal velocity, or drive, for future emergency escape parachutes has recently been reduced to not more than 50% of the vertical rate of descent.

Canopy cloth area/drag efficiency is the principal parameter of importance when landing rates of descent are considered, since cloth area is normally restricted by assembly maximum bulk and weight limitations. The simple flat circular parachute is surprisingly efficient in this respect and this together with its simple construction no doubt accounts for its continued use for airborne forces parachute systems.

Round parachutes incorporating drive slots and glide capability, can, due to the altered pressure distribution on the canopy achieve lower and more uniform vertical rates of descent than conventional unslotted parachutes of the same size. If slot

control lines are fitted the parachute can then be steered to advantage to select a desirable landing area or to land into wind with a low forward speed relative to the ground.

Current ram air gliding parachutes achieve relatively high horizontal velocities, but in this case means of incidence control are fitted to enable the parachutist to flare out on landing and hence achieve very low rates of descent at touchdown. This aspect of ram air performance is discussed more fully in a following section.

While considering landing if the parachute fails to open or if during airborne forces operations parachutists collide and become entangled a parachutist can have a very hard landing indeed! To cater for such an emergency all airborne forces parachutists carry a reserve parachute, for use in an emergency, normally mounted on the chest. A high standard of reliability is required of all airborne forces parachutes systems and this is particularly so in the case of the reserve. Here the problem is mainly one of rapid deployment at the low descent speeds which can occur with a partially malfunctioned main, and the avoidance of entanglement between the inflating reserve parachute with the retained malfunctioned main. Critical rates of descent with a partially inflated main are around 15 m/s, a descent rate which can lead to severe landing injuries, if not fatalities, but where there is very little airspeed to stream the reserve.

Considerable improvement in reserve performance has recently been achieved by the new Irvin PR7 reserve which incorporates a spring-loaded kicker board to forcibly deploy the reserve and a rubber ring fitted in the canopy crown area to rapidly increase the crown to a diameter which prevents entanglement with the rigging lines of the malfunctioned main.

7 RAM AIR GLIDING PARACHUTE

One of the most interesting and potentially important parachute developments in recent years is the ram air gliding parachute. The ram air parachute differs from conventional designs in that when inflated it resembles a low aspect ratio wing (Fig 9). It is however entirely constructed of fabric, which allows it to be packed in the same way as a conventional canopy. The leading edge of the wing is open so that ram air pressure maintains the wing shape in gliding flight. Means of pitch and bank control are provided by steering lines attached to the trailing edge of the canopy; turn control is effected by an asymmetric pull on the steering lines and angle of incidence control and flare out accomplished by an even pull.

Because of its glide capability and controllability the ram air parachute offers considerable scope for the delivery of troops - who can fly themselves to a target, and also for the delivery of supplies or weapons to a given point, under radio control or by automatic control linked to a guidance system.

The moments and forces acting on a ram air parachute in flight are shown diagrammatically in Fig 10. As drawn the parachute is gliding from left to right with a velocity V at a glide angle to the horizontal γ.

Resolving the forces on the system horizontally and vertically

$$L_c \sin\gamma - (Dc + Ds)\cos\gamma = 0$$

$$m_s g - L_c \cos\gamma - (Dc + Ds)\sin\gamma = 0 \ .$$

From the first equation it can be shown that the tangent of the glide angle γ is equal to $1/L/D$, where L/D is the overall lift/drag ratio; a familiar relationship for aerodynamic efficiency in gliding flight. Therefore in still air the glide angle, and hence the glide distance for a given height loss, is a function only of the lift drag ratio.

From combination of the two force equations it can be shown that

$$V = \left\{\frac{2}{\rho}\ \frac{W}{s}\ \frac{\cos\gamma}{C_L}\right\}^{\frac{1}{2}}$$

and hence velocity down the flight path is dependent on wing loading W/s and air density.

The system is arranged to fly at the angle of incidence corresponding to optimum L/D by rigging the canopy, that is by positioning the store and hence the centre-of-gravity of the system, such that the equilibrium attitude is at the optimum angle of incidence α. The parachute will be in stable equilibrium when the sum of the moments acting on the system is zero and when, with the sign conventions adopted, the slope of the pitching moment curve $dC_M/d\alpha$ is negative - that is when any small disturbance results in a restoring couple.

In a typical system the rigging angle ϕ could be 2°, resulting in the system flying with a wing angle of incidence α of around 8°. Rigging the canopy with ϕ too high results in a lower trim angle of incidence and a fall-off in performance; setting ϕ too low may lead to the trim angle being beyond the stall and a considerable drop in performance with severe control problems.

Any improvement in overall gliding performance is very dependent on reducing drag and one of the recommendations made by RAE in Ref 13 is for the use of small diameter Kevlar suspension lines. This not only reduces drag but the low extensibility under load improves rigging accuracy. If Kevlar lines are combined with bifurcation of lines near the wing together with a reduction in current wing thickness chord ratios, estimates indicate that improved L/D of about 3.3 should be possible, with an aspect ratio 2.0 wing.

Increase of aspect ratio, which theoretically should improve L/D and hence glide angle, has so far proved disappointing in practice, for as the span increases so do the required number of suspension lines and hence line drag; also due to the flexible nature of the wing surface, control reversal and 'end cell collapse' problems can be accentuated. Research in this area is however continuing, as the potential improvements in glide performance are considerable.

Typical horizontal velocities achieved with man carrying ram air parachutes in gliding flight are around 12 m/s and hence wind effects on gliding distances achieved can be large.

Using the relationships derived earlier, and noting that incremental displacements in the x and z directions, dx and dz, in time dt may be written

$$dx = (u + u_w)dt \qquad \text{and} \qquad dz = w dt$$

(where u_w is the horizontal wind velocity and $u = V \cos \gamma$ and $w = V \sin \gamma$) flight trajectories may be calculated. Fig 11, extracted from Ref 13, illustrates the effect of 10 m/s head and tail winds on the flight trajectories of four systems; a current man carrying ram air parachute system, the same system with reduced wing loading (m_s = 100 kg), with a 10% reduction in drag coefficient, and the current system with half brakes applied (by pulling down evenly on the control lines). In each case flight commences at 8000 metres altitude. The large effect of wind on performance is apparent and it is clear that large glide distances can only be obtained with man carrying ram air parachutes when there is a tail wind. An improvement in aerodynamic efficiency is shown to improve performance under all conditions. It is also obviously better to fly at half brakes in a following wind for maximum glide distance and to resume the zero brake configuration for wind penetration.

Work at RAE has also included a theoretical investigation of pitch stability of ram air parachutes, based on a two-dimensional model. Ref 13 shows that trailing-edge deflection is an effective means of changing glide angle and that stall recovery can be effected by returning to zero deflection. It is also shown that the flare manoeuvre, if correctly executed, is particularly effective in achieving low vertical and horizontal velocities at touchdown and that pitching oscillations are damped.

8 CONCLUSIONS

Many new applications of the parachute have been developed in recent years, for example, in addition to unconventional designs for emergency escape parachutes, very sophisticated parachute systems have been used for recovery of space capsules and ram air gliding parachutes for delivery of paratroops.

Considerable advances have been made in supporting parachute technology, in the United Kingdom important advances have been made in the prediction of parachute inflation loads and methods of controlling inflation, in formulating design rules for ram air gliding parachutes, and in the use of new materials in parachute construction. Parachute test techniques continue to improve and air launched parachute test vehicles, such as those developed at the RAE, have now become a sophisticated and reliable method of obtaining full scale performance data.

Steady progress is being made in the field of parachute stability analysis and in particular new techniques of measuring parachute apparent mass characteristics have been devised by the University of Leicester. Our knowledge of canopy stress analysis has grown only modestly and further work is required in this field. The potential of the ram

air gliding parachute is such that further research work in this area promises to lead to significant performance improvements in the future.

Acknowledgments

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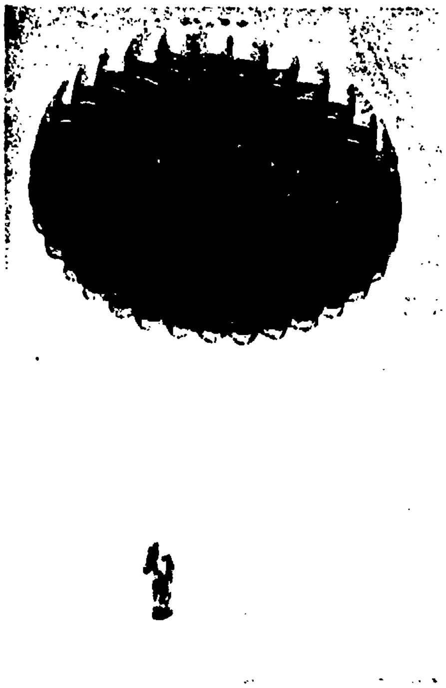
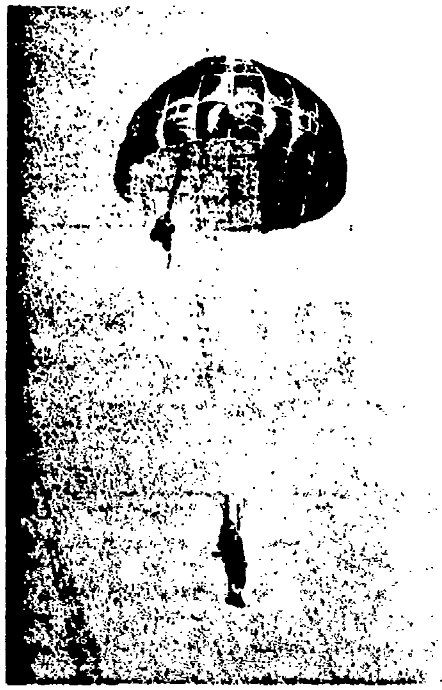
13	J.S. Lingard	The performance and design of ram air gliding parachutes. RAE Technical Report 81103 (1981)



(a) Paratroop



(b) Emergency escape

(c) Cruciform

(d) Gliding ram air

Fig 1a-d Types of parachute

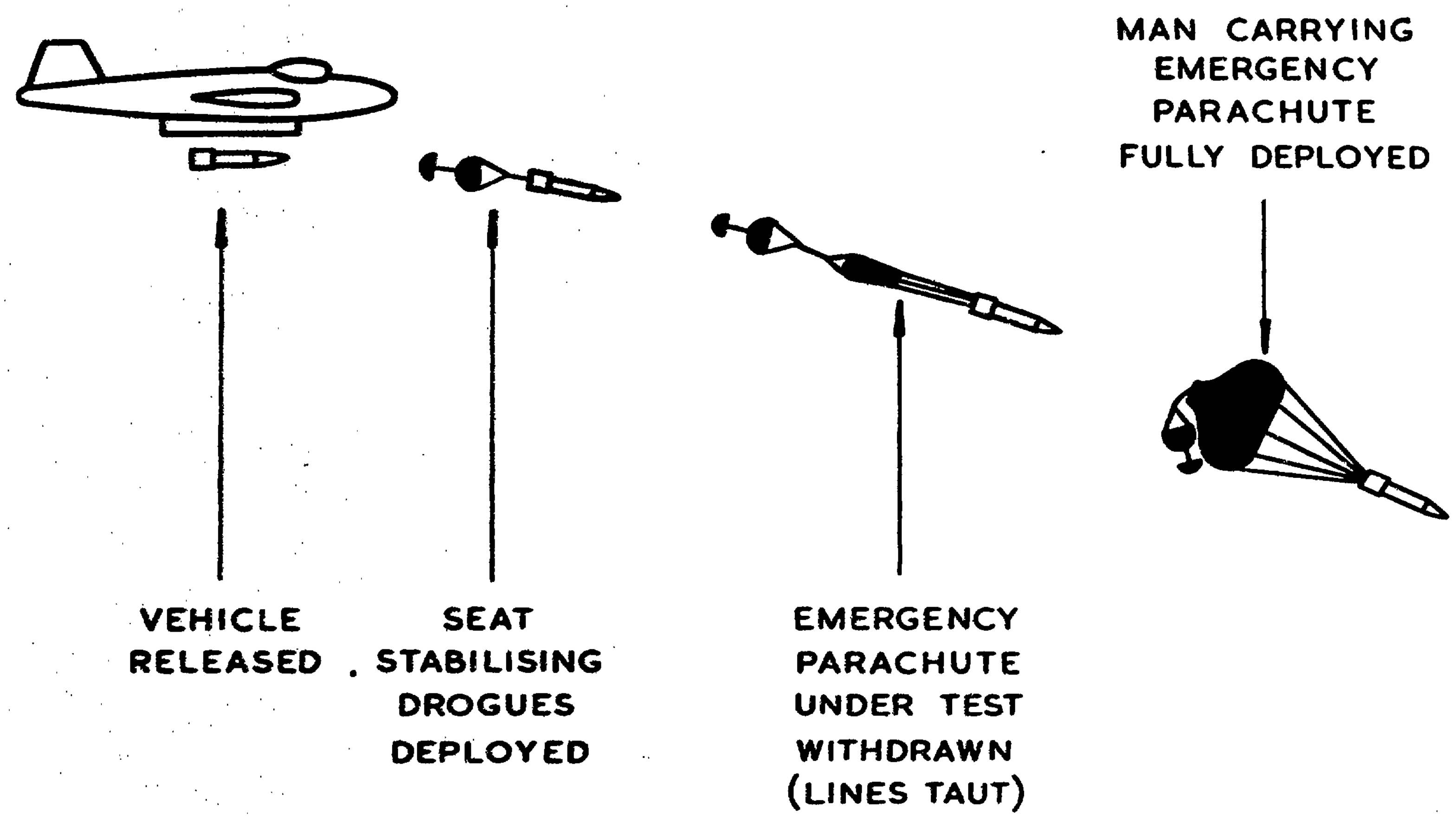


Fig 2 Deployment sequence, parachute test vehicle

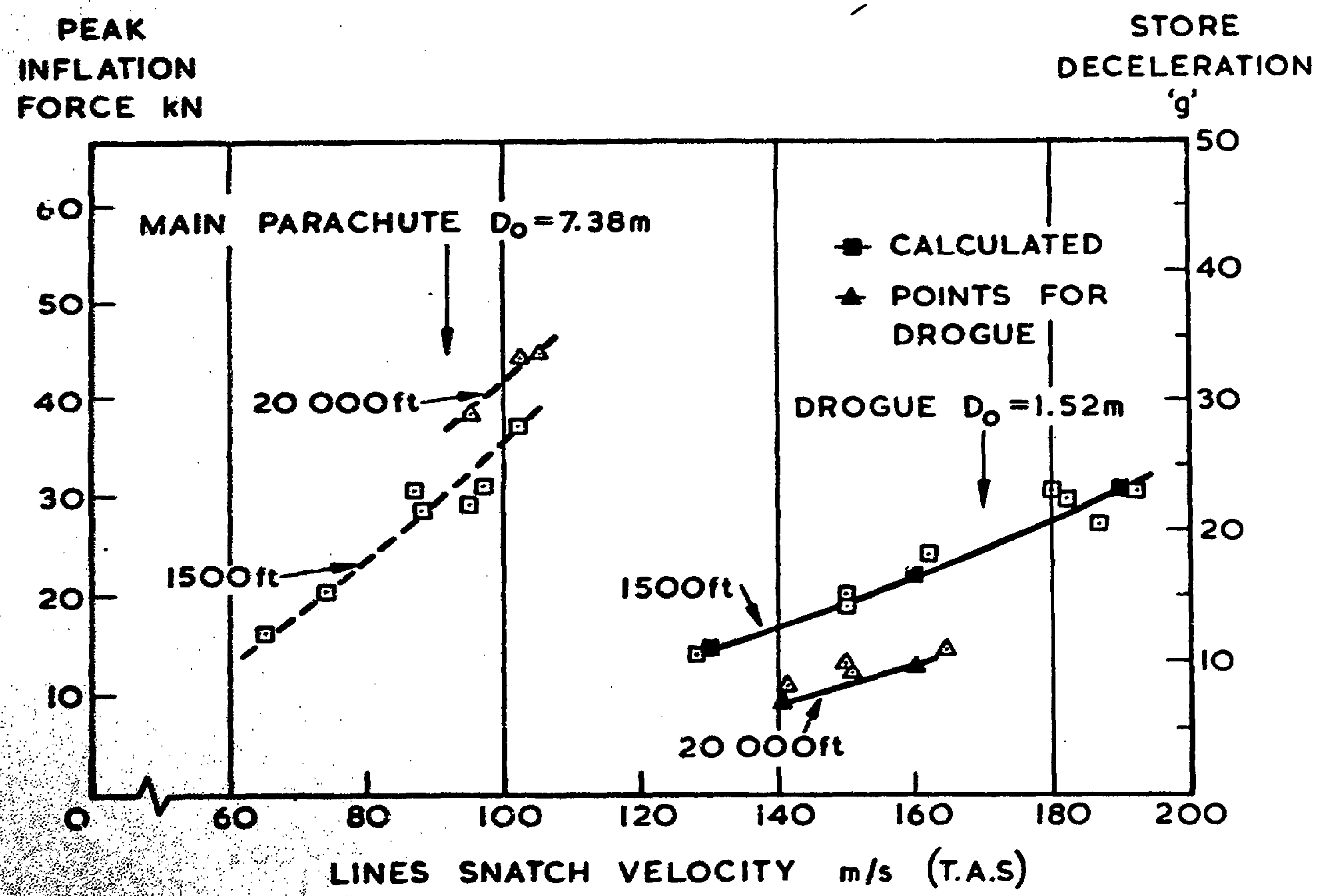


Fig 3 Parachute inflation loads

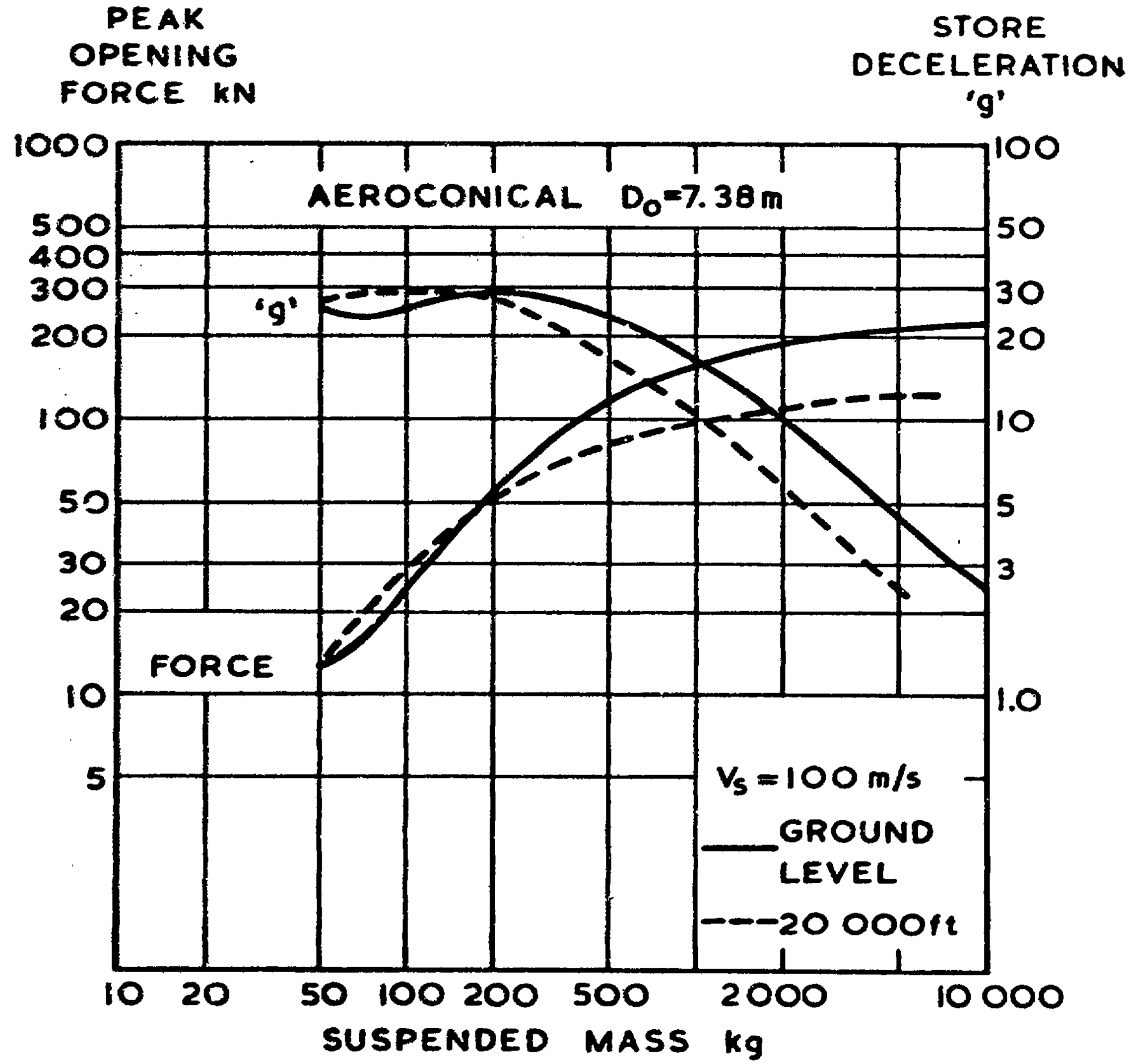


Fig 4 Effect of suspended mass

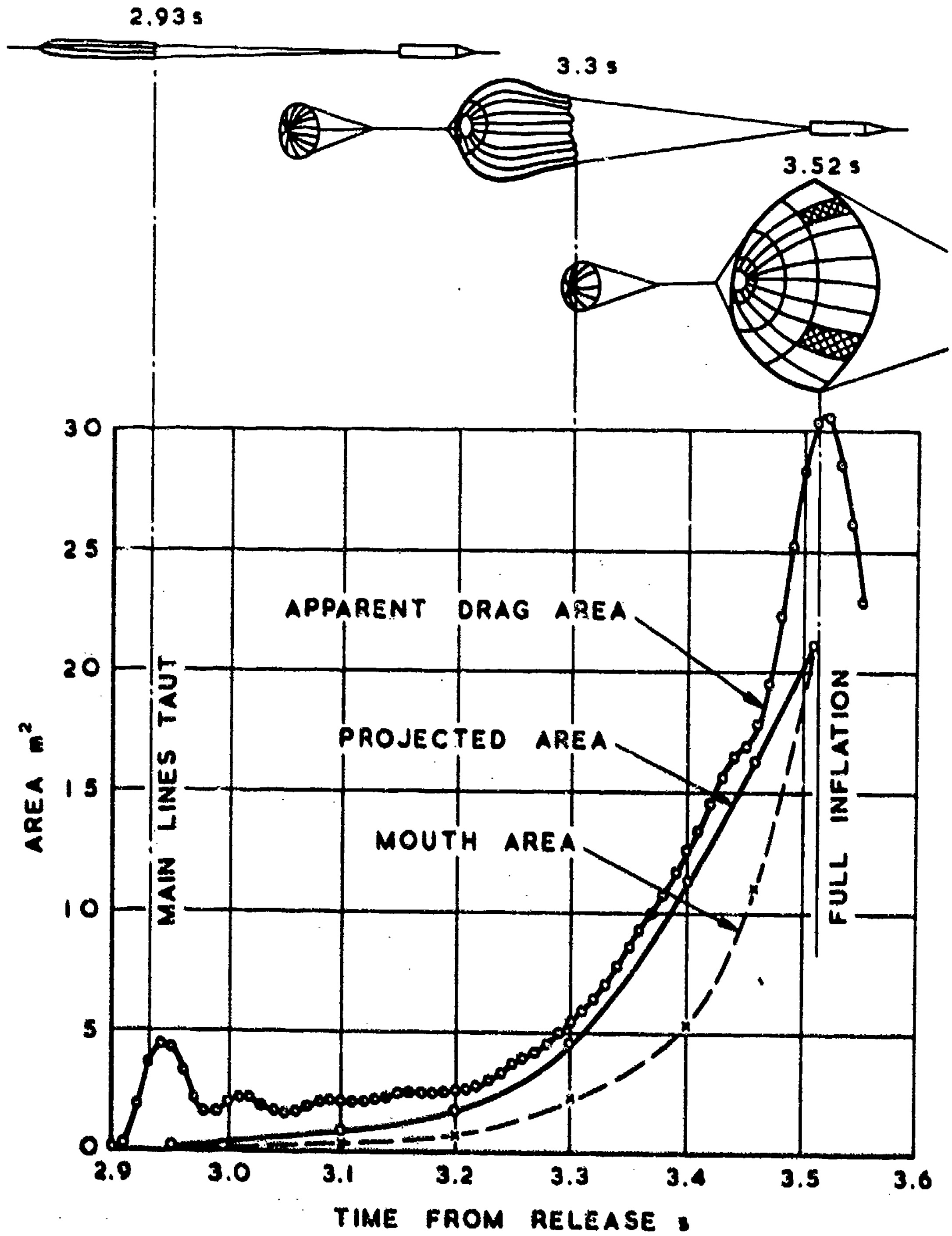


Fig 5 Parachute inflation characteristics

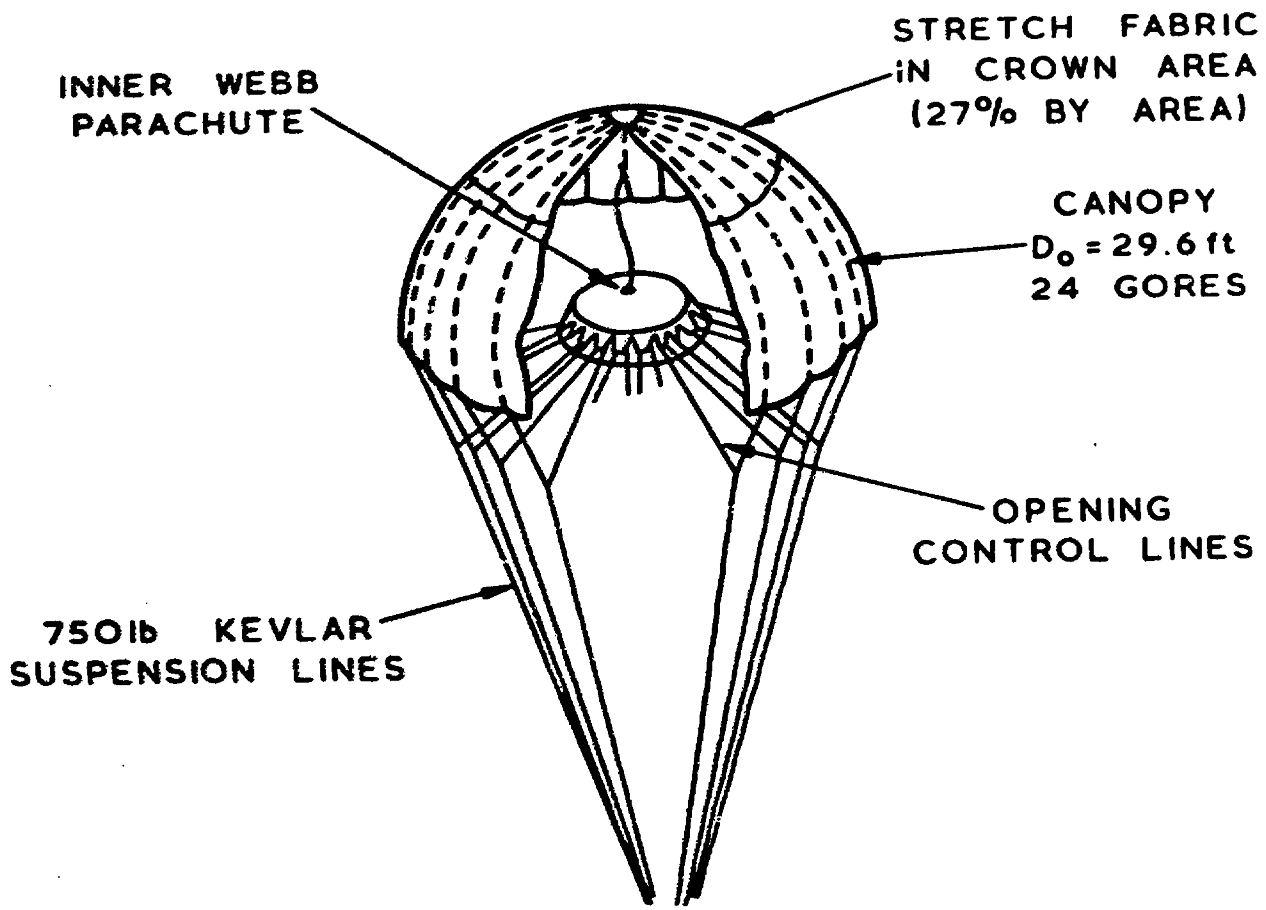


Fig 6 Aim parachute

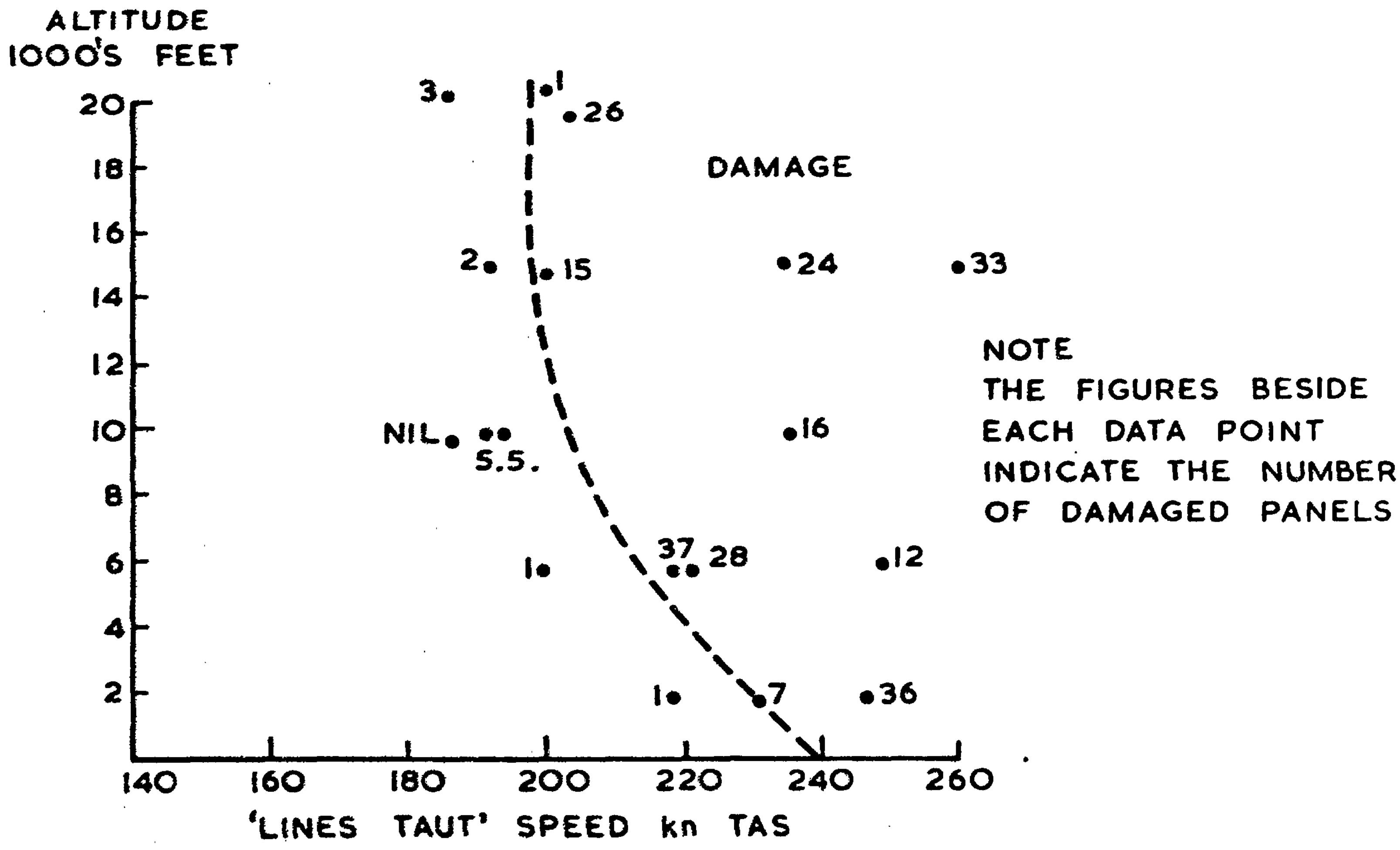
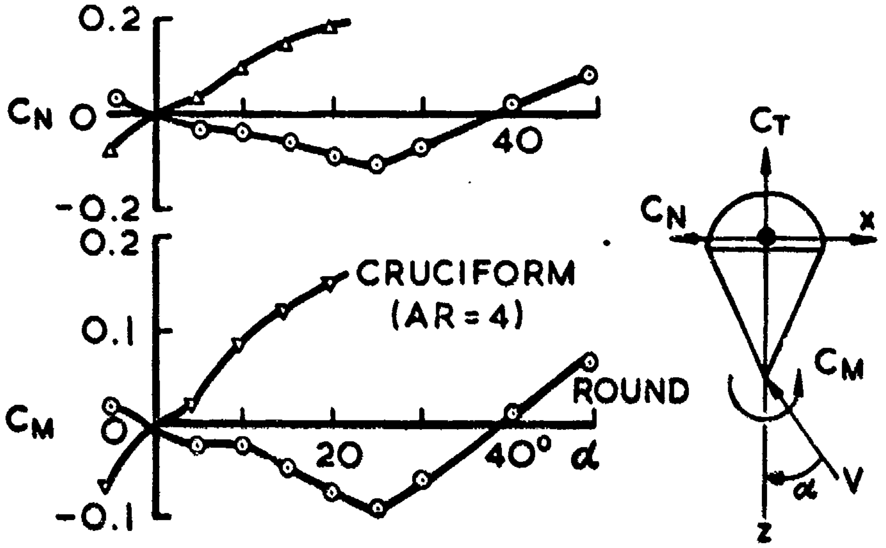
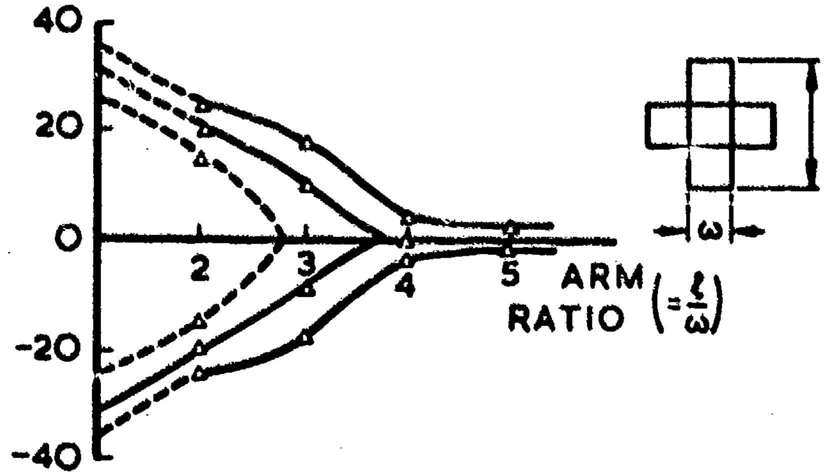


Fig 7 Aeroconical parachute - damage boundary

Fig 8a&b



(a) Aerodynamic coefficients vs α



(b) Trim angle vs arm ratio

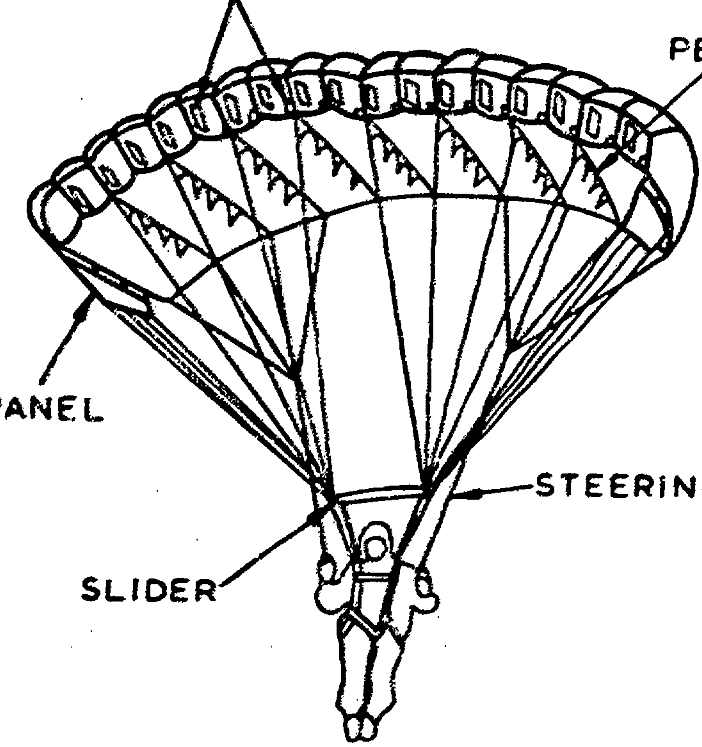


Fig 9 The ram air parachute

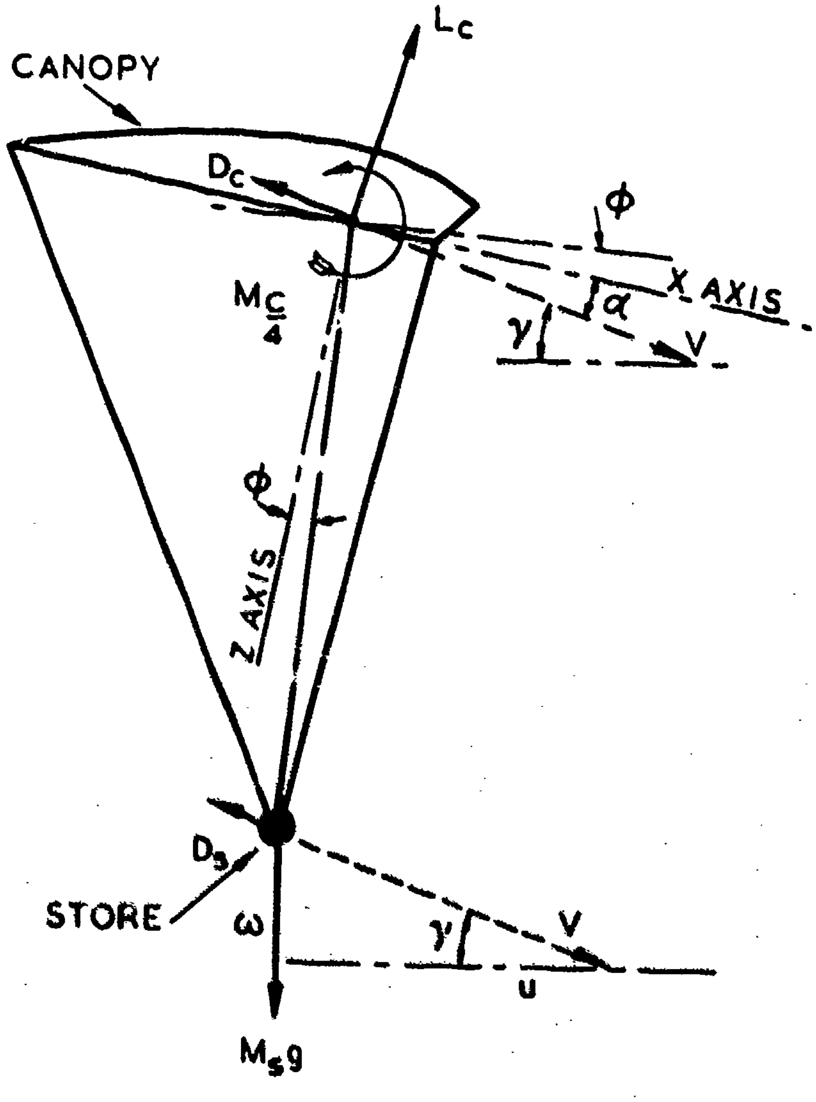


Fig 10 Forces and moments on a ram air parachute in gliding flight

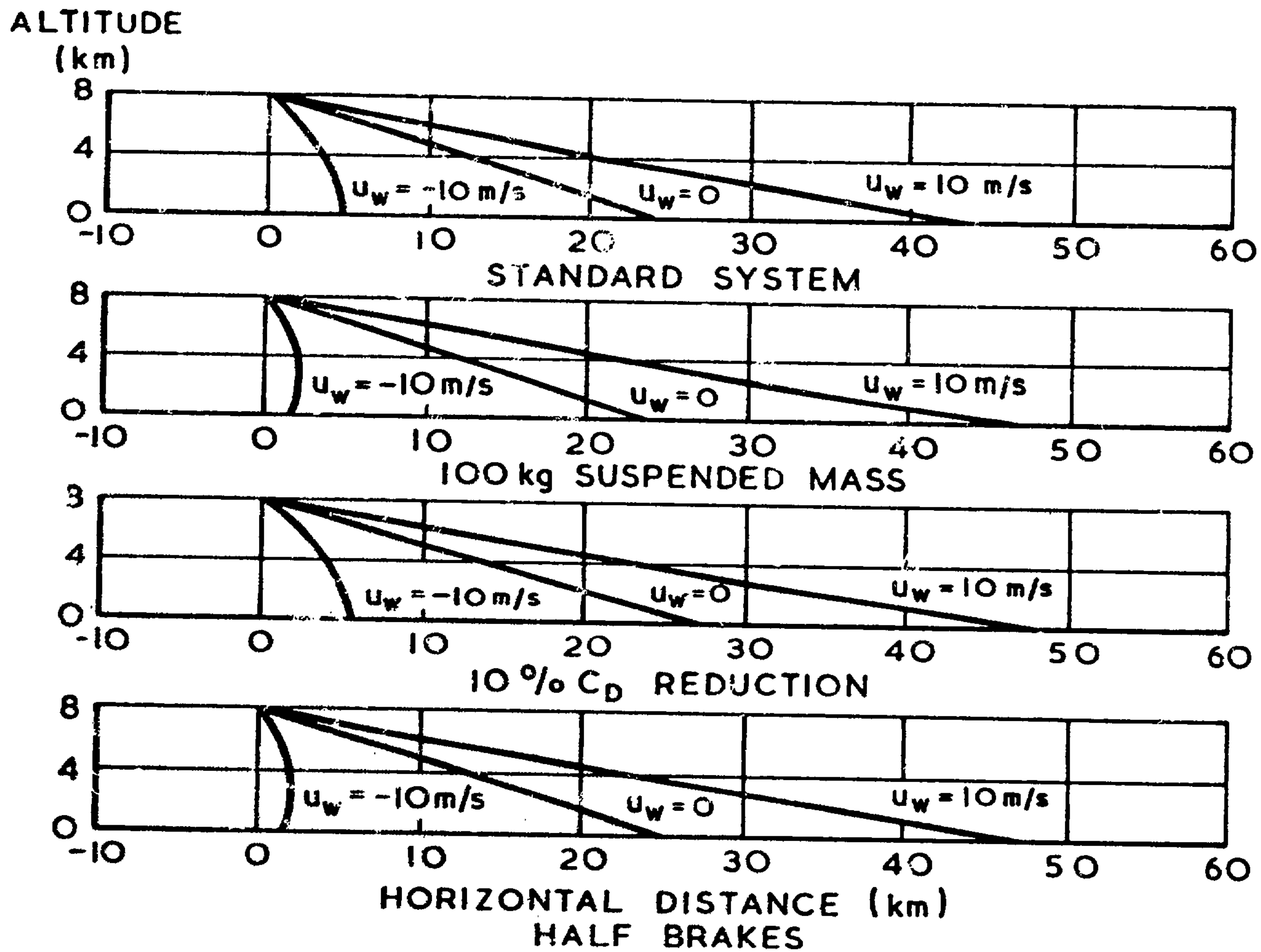


Fig 11 Flight trajectories for various wind conditions

REPORT DOCUMENTATION PAGE

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Parachutes.

17. Abstract

Many new applications of the parachute have been developed in recent years. In addition to unconventional designs for emergency escape parachutes sophisticated parachute systems have been used for recovery of space capsules and ram air gliding parachutes for the delivery of men and equipment.

In the UK important advances have been made in the prediction of parachute inflation loads, in formulating design rules for ram air gliding parachutes and in the use of new materials in parachute construction. Test techniques continue to improve and aircraft launched parachute test vehicles have become a reliable method of obtaining performance data. Progress is being made in stability analysis and new techniques devised for obtaining basic data.

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